National Aeronautics and Space Administration

NASA's New Thermal Management Systems Roadmap; What's in it, What it Means

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22 March, 2016

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Abstract

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In July of 2015 NASA publically released a new set of Technology Area Roadmaps that will be used to help guide future NASA-funded technology development efforts. One of these was the Thermal Management Systems Roadmap, often identified as TA14. This Roadmap identifies the time sequencing and interdependencies of high priority, advanced thermal control technology for the next 5 to 20 years.

Available funding limits the development of new technology. The Roadmaps are the first step in the process of prioritizing HQ-supported technology funding. The 2015 Roadmaps are focused on planned mission architectures and needs, as identified in the NRC-led science Decadals and HEOMD's Design Reference Missions. Additionally, the 2015 Roadmaps focus on "applied " R&D as opposed to more basic research.

The NASA Mission Directorates were all closely involved in development of 2015 Roadmaps, and an extensive external review was also conducted.

This talk will discuss the Technology Roadmaps in general, and then focus on the specific technologies identified for TA 14, Thermal Management Systems.

Introduction to Technology Roadmaps

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Technology Portfolio Management

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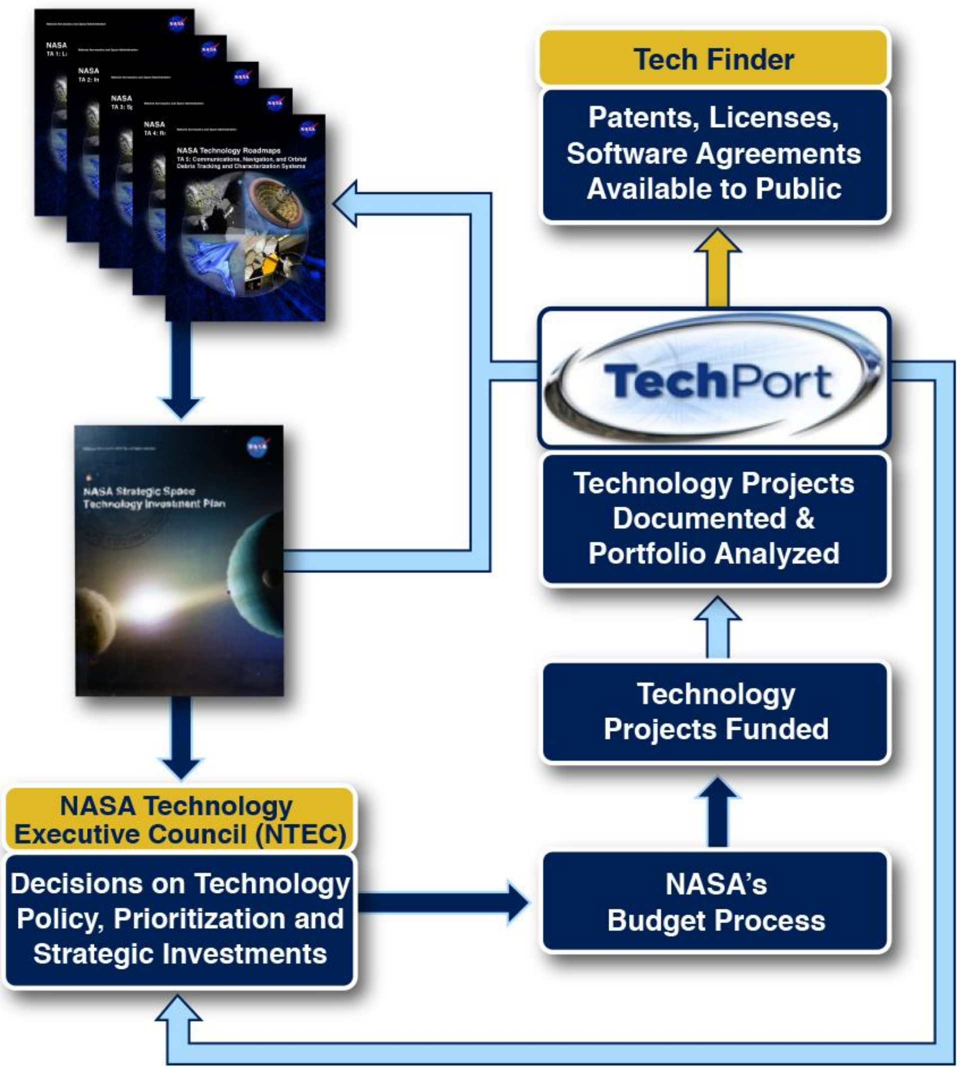
Roadmaps – A set of documents that consider a wide range of **needed technologies** and development pathways for the next 20 years. The roadmaps focus on “applied research” and “development” activities.
http://www.nasa.gov/offices/oct/home/roadmaps/index.html

Strategic Technology Investment Plan (STIP)– An actionable plan that lays out the **strategy** for developing the technologies essential to the pursuit of NASA’s missior and achievement of National goals. This plan provides the **prioritization** and guiding principles of investment for the **technologies identified in the roadmaps.**

NASA Technology Executive Council (NTEC) - NASA's senior **decision-making body** for technology policy, prioritization, and strategic investments.

TechPort – Web-based software system that serves as NASA’s integrated **authoritative technology data source and decision support tool**. Provides information on technology programs and projects.
http://techport.nasa.gov



Introduction to Technology Roadmaps

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Roadmaps

What We Could Do

SSTIP (Priorities)

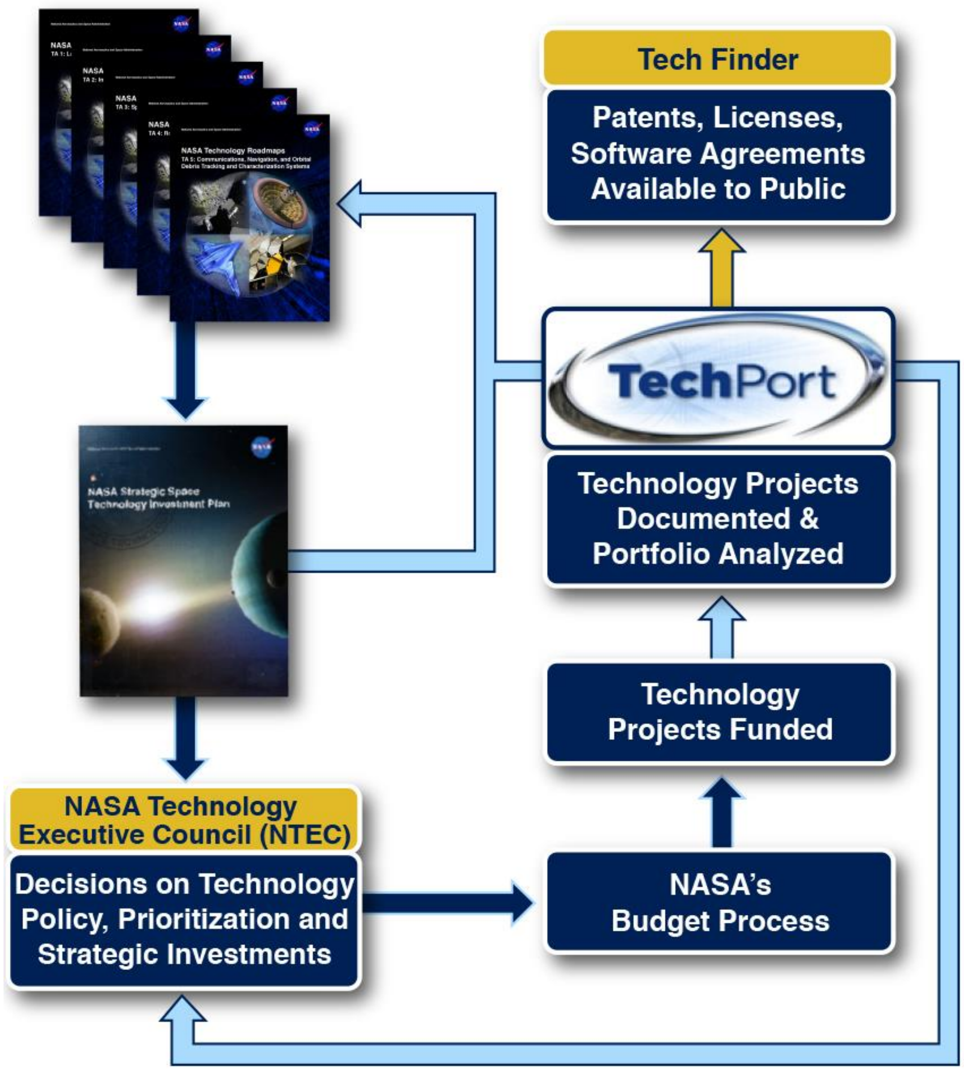
What We Should Do

NTEC and Budget Process

What We Will Do

TechPort

What We Are Doing



2015 NASA Technology Roadmap

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Technology Roadmap Updated

Considers
- Updates in Science Decadal surveys
- Human Exploration capability work
- Advancements in technology

Includes:
- State-of-art
- Capability needs
- Performance goals

Expanded Scope:
- ✓ Aeronautics technology
- ✓ Autonomous systems
- ✓ Avionics
- ✓ Information technology
- ✓ Orbital debris
- ✓ Radiation
- ✓ Space weather

2015 Technology Roadmaps Facts:

340 people contributed (authored content)
This included input from all NASA Centers, organizations, industry and government. Others provided edits during Center and HQ reviews.

The 2015 NASA Technology Roadmaps are comprised of:
- 16 sections
- 15 technology areas
- 2,100 pages
- 1,278 technology candidates

Since the 2012 Roadmaps were released, the 2015 Roadmaps have been expanded to include: **44 new level 3 Space Technology Areas** that will be evaluated by the NRC.

Technology Areas: 1, 4, 5, 7, 9, 11, 13, and 14

2015 NASA Technology Roadmap Reflected Changing Needs

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Include updates in new Human Exploration, Science, and Aeronautics mission needs:

- Human Exploration mission classes and design reference missions derived from Capability-Driven Framework and Human Spaceflight Architecture studies
- Science mission classes and design reference missions derived from decadals and Science plans
- Aeronautics content from Thrust Areas and Aeronautics Research and Development Plans

NASA relies on the science community to identify and prioritize leading-edge scientific questions and the observations required to answer them. One principal means by which NASA's Science Mission Directorate engages the science community in this task is through the National Research Council (NRC).

2013 – Visions and Voyages for Planetary Science*

2012 – Solar and Space Physics: A Science for a Technological Society*

2010 – New Worlds, New Horizons in Astronomy and Astrophysics*

2007 – Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond

* **The top three of the Decadal surveys are new and have influenced the Technology Roadmap updates**

Technology Roadmap Based On NASA's Capability Driven Framework

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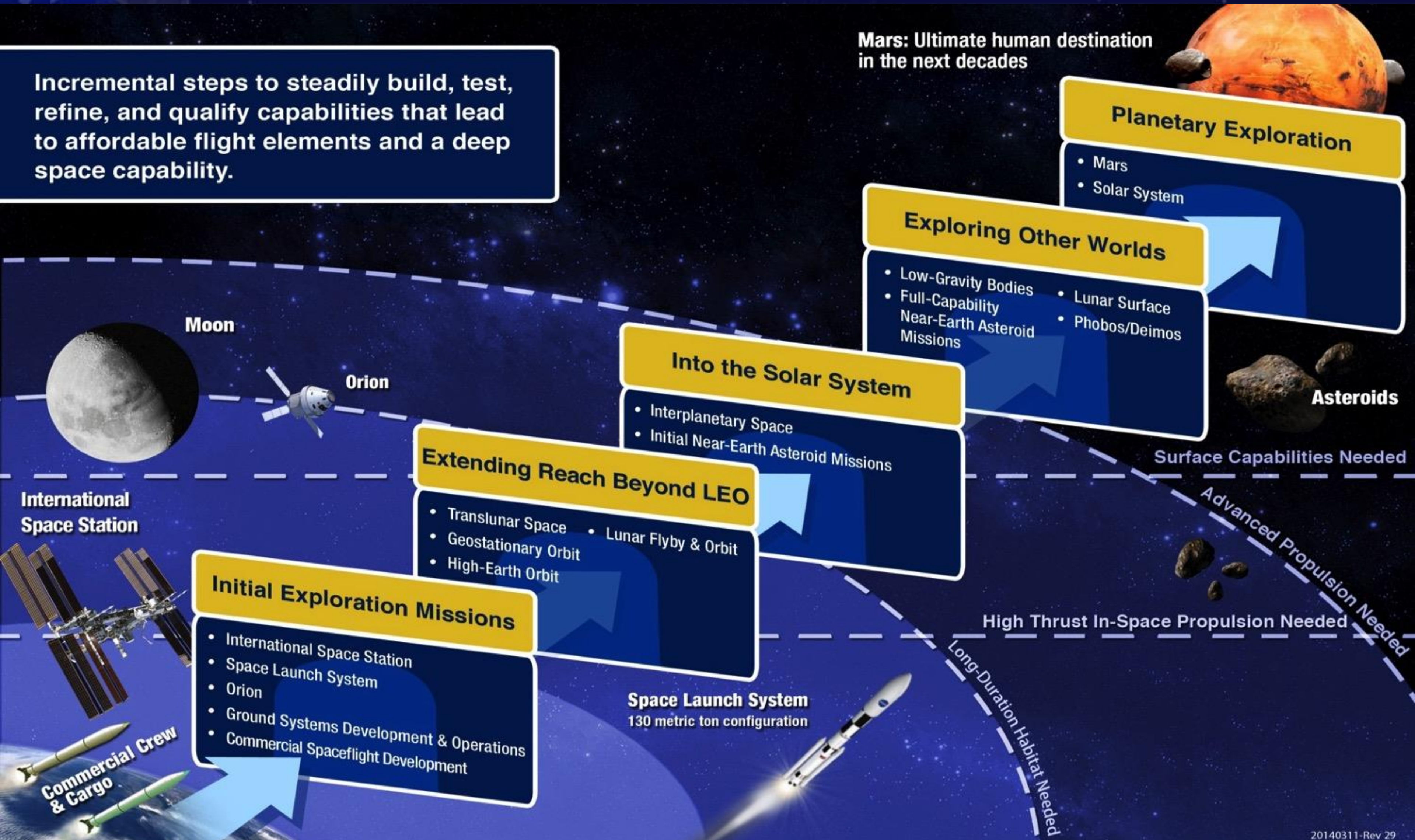

15 Technical Area Sections General Format

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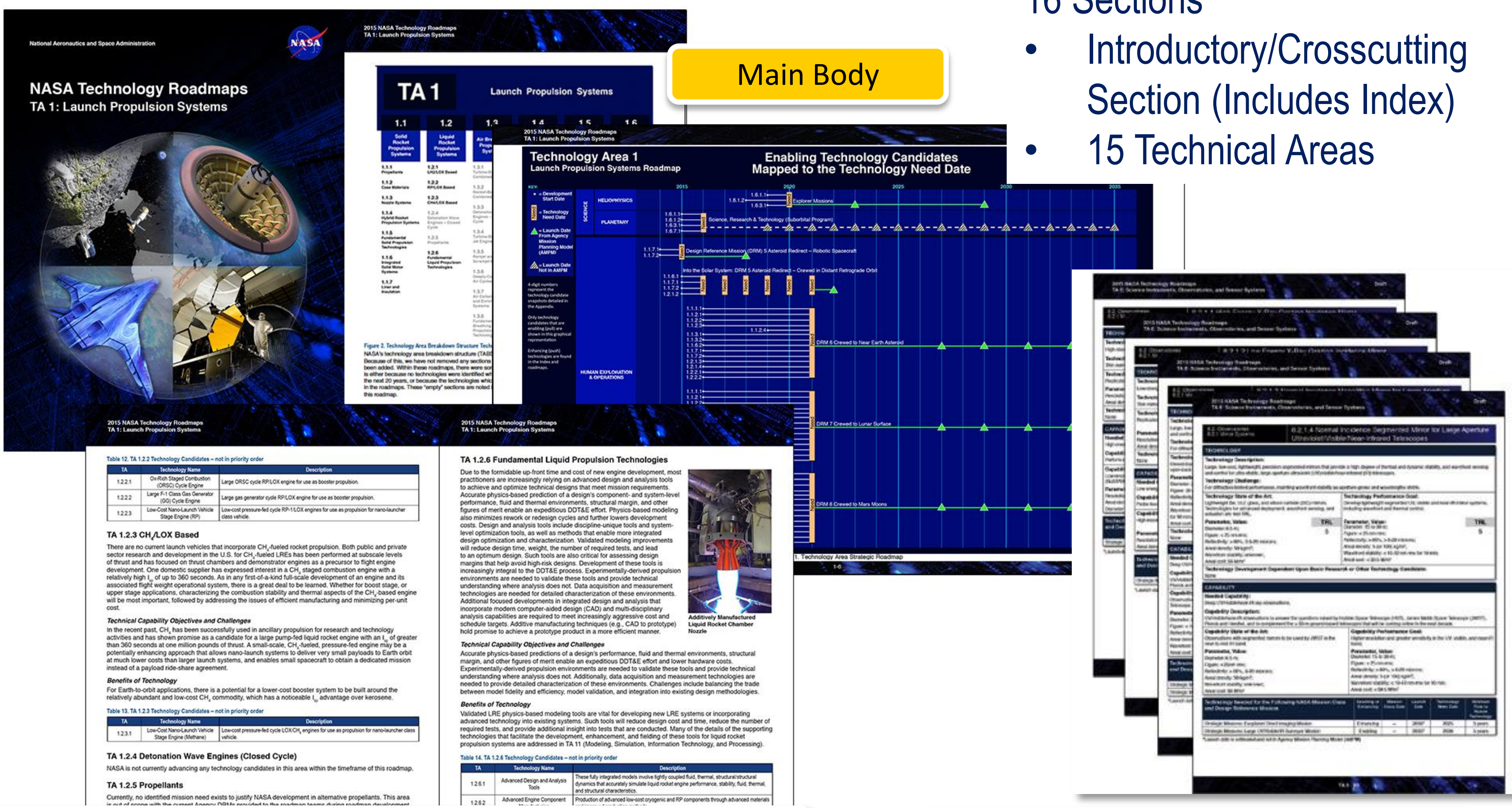
16 Sections
- Introductory/Crosscutting Section (Includes Index)
- 15 Technical Areas



Find the roadmaps at:
www.nasa.gov/offices/oct/home/roadmaps/index.html

TA 14: Contributors

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TA 14: Contributors (continued)

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2015 Draft Technology Roadmap External Review

2015 draft Technology Roadmaps Released to the Public on May 11, 2015

- Press Release
- Federal Register
- FedBiz Ops
- Request for Information
- Multiple news stories followed

77 Letters Sent by NASA Announcing Release and Requesting Input:

- Other Government Agencies
- Commercial Industry Associations
- Academic Institutions
- International Partners

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NASA Technology Roadmap: A Heavenly Guide For IT And CIOs

NASA's Technology Roadmap for 2015-2035 gives hints about the future of IT in your enterprise. Here's how space is changing big data, supercomputing, and other technologies.

2 of 16

Flight Computing

There are two major issues with flight computing that NASA needs to address, but that enterprise IT also might be interested in -- data triage and hardened computing. Space flights pull in a lot of data. Not all of that data can be transmitted back effectively at this point, especially if transmission times are limited by the orbit of the craft or the planets. How to send the right data at the right time will matter, especially as craft get farther from the earth. That's going to become an increasingly important issue for enterprises as the Internet of Things explodes as well. Pulling the right data at the right time to make real-time decisions is going to get harder, but more important, as data sources explode.

NASA also needs radiation-hardened computers. You might not need

Other Government Input to Roadmaps

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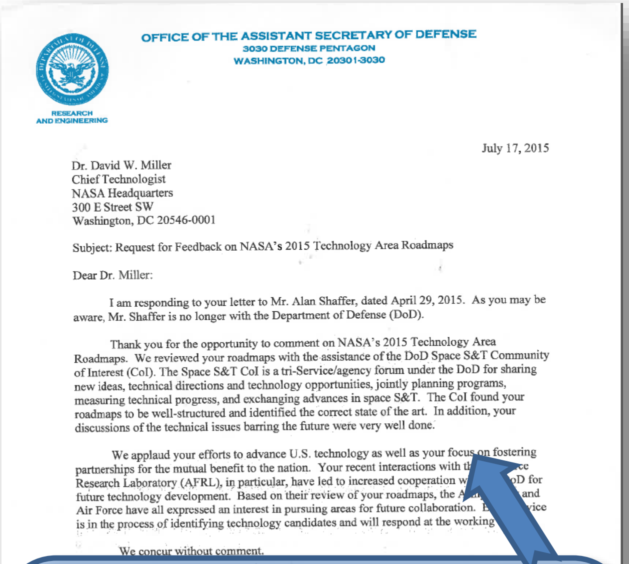
Constructive and positive feedback on roadmaps from review

Two rounds of reviews coordinated with other government agencies. Examples of participants:

- July 2014 review of draft:
  - Department of Defense
    - US Army Development and Engineering Center
    - Air Force Research Laboratory (AFRL)
    - Office of the Secretary of Defense/Acquisition, Technology & Logistics
    - Air Force Space and Missile Test Branch
  - U.S. Department of Energy
  - Department of Transportation, Federal Railway Administration
  - National Oceanic and Atmospheric Administration (NOAA)
- May 2015 review:
  - AFRL
  - Defense Advanced Research Projects Agency (DARPA)
  - Missile Defense Agency (MDA)
  - Department of Transportation, Federal Aviation Administration (FAA)
  - NOAA



OFFICE OF THE ASSISTANT SECRETARY OF DEFENSE
3030 DEFENSE PENTAGON
WASHINGTON, DC 20301-3030

RESEARCH AND ENGINEERING

July 17, 2015

Dr. David W. Miller
Chief Technologist
NASA Headquarters
300 E Street SW
Washington, DC 20546-0001

Subject: Request for Feedback on NASA's 2015 Technology Area Roadmaps

Dear Dr. Miller:

I am responding to your letter to Mr. Alan Shaffer, dated April 29, 2015. As you may be aware, Mr. Shaffer is no longer with the Department of Defense (DoD).

Thank you for the opportunity to comment on NASA's 2015 Technology Area Roadmaps. We reviewed your roadmaps with the assistance of the DoD Space S&T Community of Interest (CoI). The Space S&T CoI is a tri-Service/agency forum under the DoD for sharing new ideas, technical directions and technology opportunities, jointly planning programs, measuring technical progress, and exchanging advances in space S&T. The CoI found your roadmaps to be well-structured and identified the correct state of the art. In addition, your discussions of the technical issues barring the future were very well done.

We applaud your efforts to advance U.S. technology as well as your focus on fostering partnerships for the mutual benefit to the nation. Your recent interactions with th ce Research Laboratory (AFRL), in particular, have led to increased cooperation w oD for future technology development. Based on their review of your roadmaps, the A and Air Force have all expressed an interest in pursuing areas for future collaboration. E vice is in the process of identifying technology candidates and will respond at the working

We concur without comment.

Sincerely,

Office of the Secretary of Defense, Director, Space and Sensors Systems Research Directorate:

"The CoI found your roadmaps to be well-structured and identified the correct state of the art. In addition, your discussions of the technical issues barring the future were very well done"

NASA's Roadmap and Strategic Space Technology Investment Plan Used During FY 2013 - FY 2015 Procurement Solicitations

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NASA is embracing the Roadmaps and Strategic Technology Investment Plan
Example Solicitations where they were cited:

STMD

NASA Innovative Advanced Concepts (NIAC) Phase II

FY 15

- Space Technology Research, Development, Demonstration, and Infusion-2015 (Spacetech-reddi-2015)
- Small Spacecraft Technology Program Smallsat Technology Partnerships
- Game Changing Development Program, Ultra-lightweight core Materials for Efficient Load-bearing Composite Sandwich Structures
- Technology Advancement Utilizing Suborbital Flight Opportunities NASA Flight Opportunities (FO)
- Sources Sought: NASA Opportunity Notice to Participate in its Centennial Challenges Program as an Allied Organization

FY 14

- Space Technology Research, Development, Demonstration, and Infusion 2014(SpaceTech-REDDI-2014)
- NASA Innovative Advanced Concepts (NAIC), Phase I, 2014 NRA
- Space Technology Research Grants Program, Early Stage Innovations, 2014 NRA
- Game Changing Development Program, Advanced Oxygen Recovery For Spacecraft Life Support Systems
- Center Innovation Fund

FY 13

- NASA Space Technology Research Fellowships (NSTRF) – Fall 2013
- Space Technology Research Opportunities – Early Stage Innovations (STRO-ESI)
- SmallSat Technology Partnerships FY13 CAN
- 2013 Cooperative Agreement Notice - Dual Use Technology Development at Stennis Space Center

HEOMD

FY 13

- Request for Information to Identify Technology Science And Exploration System Demonstration Payloads

Other

FY 15

- Cooperative Agreement Notice (CAN) 2015 Technology Advancing Partnerships (TAP) Call At NASA John F. Kennedy Space Center
- Cooperative Agreement Notice (CAN) 2015 Experimental Program To Stimulate Competitive Research (Epscor)

FY 14

- Experimental Program to Stimulate Competitive Research (EPSCoR)
- Technology Advancing Partnerships (TAP) Challenge at NASA John F. Kennedy Space Center, Cooperative Agreement Notice (CAN) 2014

FY 13

- Propulsion Technical Expertise Technical Information Management and Logistical Support of the National Institute for Rocket Propulsion Systems and the Joint Army Navy Air Force Subcommittees

Note**: SMD's** ROSES procurement in FY 2016 will ask for submissions to identify Technology Roadmap TA's for each submission

TA 14: Thermal Management Systems

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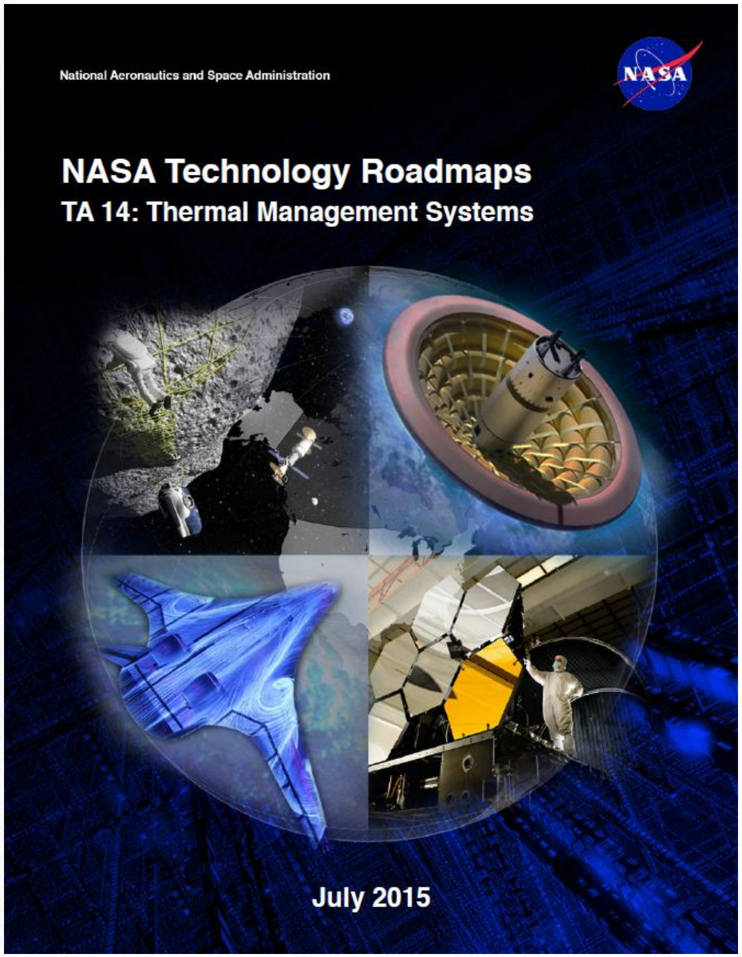

- Acquire, transport, and reject heat, as well as insulate and control the flow of heat to maintain temperatures within specified limits. Virtually all spacecraft and related equipment require some level of thermal control, some much ore tightly controlled than others, and the design approach and technologies employed vary widely depending on application.
- This Technology Area includes:
  - 3 level 2 technology areas
  - 55 technology candidates
    - 23 enabling
    - 36 enhancing

TA 14: Technology Area Breakdown Structure

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TA 14 Thermal Management Systems

14.1 Cryogenic Systems

14.1.1 Passive Thermal Control

14.1.2 Active Thermal Control

14.1.3 Integration and Modeling

14.2 Thermal Control Systems

14.2.1 Heat Acquisition

14.2.2 Heat Transport

14.2.3 Heat Rejection and Energy Storage

14.3 Thermal Protection Systems

14.3.1 Ascent/Entry TPS

14.3.2 TPS Modeling and Simulation

14.3.3 TPS Sensors and Measurement Systems

Technology Candidates Mapped to Missions They Enable (Development, Integration, Launch) TA 14

National Aeronautics and Space Administration

TA 14: Thermal Management Systems

Discovery 14, Explorer

DRM 5 Crewed, New Frontiers 4,

DRM 6, 7, 8,

Io Observer

8a, 9, 9a,

Technology Area 14	Candidate #	Design Reference Mission
Cooled Insulation for Reduced and Zero Boil-Off	14.1.1.4	6, 7, 8, 8a, 9, 9a
High-Capacity 20 Kelvin Cryocoolers	14.1.2.1	6, 7, 8, 8a, 9, 9a
High-Capacity Cryocoolers for In-Situ Manufacture of Cryogenic Fluids	14.1.2.3	9
Low-T, Low-Q Cryocoolers	14.1.2.4	Far IR Surveyor
Integrated Radiator/Cryocooler for Liquefaction	14.1.2.7	7, 9
Subcooling Cryogenic Propellants	14.1.2.8	Explorer Missions, Europa, New Frontiers 4
Freeze-Tolerant Heat Pipes	14.2.1.1	6, 8
Heat Transport Fluid	14.2.2.1	5 Crewed
Two-Phase Pumped Loop System	14.2.3.2	9, Discovery 14, Io Observer
Phase-Change Heat Exchanger - Phase Change Material Thermal Storage (Heat Sinks & Storage)	14.2.3.3	5 Crewed, New Frontiers 4
Evaporative Cooling	14.2.3.4	9, 9a
Freezable/Stagnating Radiator (Variable Heat Rejection Radiator Technology)	14.2.3.5	5 Crewed
Variable-Geometry Radiators (Variable Heat Rejection Radiator Technology)	14.2.3.6	5 Crewed
Variable-Emissivity Radiator (Variable Heat Rejection Radiator Technology)	14.2.3.7	5 Crewed
Radiator Repair	14.2.3.8	5 Crewed, 6, 7, 8, 8a, 9, 9a
80-250 Degrees © Variable Conductance Heat Pipe Radiator	14.2.3.9	9

FY14 FY15 FY16 FY17 FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26 FY27 FY28 FY29 FY30 FY31 FY32 FY33 FY34 FY35

Earliest Required Start Date | Earliest Technology Need Date | Launch Dates in AMPM | Launch Dates not in AMPM

Development | Integration | Launch

Technology Candidates Mapped to Missions They Enable (Development, Integration, Launch) TA 14

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Technology Area 14	Candidate #	Design Reference Mission	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35
TA 14: Thermal Management Systems											DRM 5 Crewed,	Discovery 14, Explorer	New Frontiers 4,			DRM 6, 7, 8,		Io Observer						8a, 9, 9a,
Planetary Lander Multi-Phase Thermal Control	14.2.3.10	Venus In-Situ																						
Rigid Ablative Thermal Protection System	14.3.1.1	5 Crewed, 6, 7, 8, 8a, 9, 9a																						
Obsolescence-Driven Thermal Protection System Materials	14.3.1.2	5 Crewed, 6, 7, 8, 8a, 9, 9a																						
Flexible/Deployable Thermal Protection System	14.3.1.3	9, New Frontiers 4																						
High Temperature Seals and Thermal Barriers	14.3.1.8	5 Crewed, 6, 7, 8, 8a, 9																						
Shock Radiation Modeling	14.3.2.2	8, 8a, 9, 9a																						
Radiometers/Spectrometers	14.3.3.1	5 Crewed, 6, 9, 9a																						

Earliest Required Start Date | Earliest Technology Need Date | Launch Dates in AMPM | Launch Dates not in AMPM

Development | Integration | Launch

Example Technology Candidate

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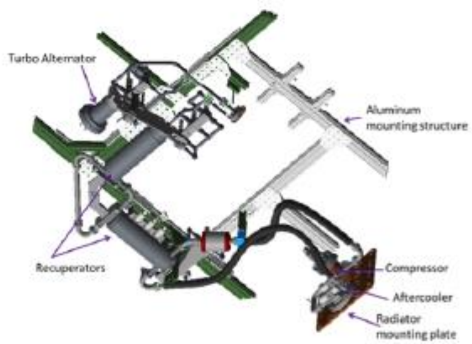
TA 14.1: Cryogenic Systems

Virtually any large-scale space mission, robotic or crewed, requires the use of cryogen propellants because of their high energy and performance. Use of liquid oxygen/liquid hydrogen systems have the highest thrust per mass flow rate, or specific impulse (I_{sp}), of any chemical propulsion technologies and have been used for many years in vehicles, including the space shuttle. However, these systems rapidly consume their propellan typically in less than 24 hours after launch, so current thermal management and insulation systems are adequate and boil-off of the propellant is acceptable. Longer-duration missions using cryogenic propellants require near-zero boil-off for all systems.

Zero boil-off for liquid oxygen has been demonstrated in large-scale ground tests, but not in a microgravity environment. For liquid hydrogen, the state of the art (SOA) evaporation rate is still on the order of two perce per day.



Technology Candidate Snapshot

14.1 Cryogenic Systems
14.1.2 Active Thermal Control

14.1.2.7 Integrated Radiator/Cryocooler for Liquefaction

TECHNOLOGY

Technology Description: High-capacity, high-efficiency, low-mass heat rejection system and controls for oxygen production on Martian surface.

Technology Challenge: Challenges include developing and flight qualifying an integrated system in a relevant environment.

Technology State of the Art: Integration of a heat pipe radiator with a reverse turbo Brayton cryocooler was recently demonstrated in a simulated space environment.

Parameter, Value:	TRL
Heat rejection at 300 K: 400 W Minimizing mass was not addressed Radiator efficiency: 0.98	5

Technology Performance Goal: Provide integrated radiator/cryocooler system for continuous liquefaction product stream at in-situ processing plant.

Parameter, Value:	TRL
Rate: liquefy 0.16 kg oxygen/hr for Lunar environment and 2.2 for Martian.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Liquefaction and storage of oxygen.

Capability Description: Provide system for continuous liquefaction product stream at in-situ processing plant.

Capability State of the Art: A flight-qualified cryocooler heat rejection system has operated on the Hubble telescope and included capillary-pumped loop heat pipes.

Parameter, Value:
Heat rejected at 300 K: 400 W
Efficiency: High
Mass: Low

Capability Performance Goal: From Constellation lunar surface architecture needed 1000 kg oxygen per year for life support needs. Per DRM 7 - 1 crew mission per year sets storage duration. From DRM 9, ISRU plant pre-deployed one opportunity before crew and all oxygen is made and in tanks before crew leaves.

Parameter, Value:
Lunar:
Rate: liquefy 0.16 kg oxygen/hr
Duration: 1 year
Mars:
Rate: liquefy 2.2 kg oxygen/hr
Duration: greater than 3.5 years from first drop of O_2 produced

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	6 years

TA 14: Goals and Sub-Goals

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14.0 Thermal Management Systems	**Goals:**	**Maintain temperatures of a sensor, component, instrument, spacecraft, or space facility within the required limits, regardless of the external environment or the thermal loads imposed from operations.**
14.1 Cryogenic Systems	Sub-Goals:	Maintain cryogenic temperatures to enable longer-duration missions that use cryogenic propellants and advance the development of cryocoolers.
14.2 Thermal Control Systems	Sub-Goals:	Maintain all vehicle surfaces and components within an appropriate temperature range throughout the many mission phases despite changing heat loads and thermal environments.
14.3 Thermal Protection Systems	Sub-Goals:	Protect spacecraft and systems during ascent through, or entry into an atmosphere.

Cryogenic Technology Candidates – *Passive Thermal Control*

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Table 3. TA 14.1.1 Technology Candidates – not in priority order

TA	Technology Name	Description
14.1.1.1	Load-Responsive Insulation	Multi-environment thermal insulation for spacecraft cryogenic propellant tanks.
14.1.1.2	Wrapped Insulation	Thermal insulation for cryogenic tubing.
14.1.1.3	Insulation with MMOD Protection	Spacecraft cryogenic propellant-tank thermal insulation with micrometeoroid and orbital debris protection.
14.1.1.4	Cooled Insulation for Reduced and Zero Boil-off	Insulation integrated with broad area cooling (BAC) shields or hydrogen vapor-cooled shields.
14.1.1.5	Modeling for Multi-Layer Insulation (MLI)	Empirical equations for low-temperature multilayer insulation.
14.1.1.6	Low Thermal Conductivity Structural Supports	Structural supports for cryogenic propellant tanks that have low heat loss.
14.1.1.7	Low-Temperature Radiators	Spacecraft radiators that have high heat rejection at very low temperatures.
14.1.1.8	Cryogenic Heat Pipes	Provide heat pipes and heat spreaders that are effective at temperatures below 50 K. Specialized applications require devices that operate below 4 K.

Cryogenic Technology Candidates –*Active Thermal Control*

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Table 4. TA 14.1.2 Technology Candidates – not in priority order

TA	Technology Name	Description
14.1.2.1	High-capacity 20 K Cryocoolers	Spaceflight cryocooler for cooling liquid hydrogen propellant tanks.
14.1.2.2	High-capacity 90 K Cryocoolers	Spaceflight cryocooler for cooling liquid oxygen propellant tanks and for broad-area cooling shield for liquid hydrogen tanks.
14.1.2.3	High-capacity Cryocoolers for In-Situ Manufacture of Cryogenic Fluids	High capacity, high efficiency, low mass cryocoolers for liquid oxygen production on the Martian surface.
14.1.2.4	Low-T, Low-Q Cryocoolers	Multi-stage, sub-Kelvin cryocoolers with high efficiency, and 4 K cryocoolers as heat sinks.
14.1.2.5	Distributed Cooling Loops	Cooling systems that reduce boil-off from cryogenic propellant tanks. May include cryogenic circulators, heat traps, and heat exchangers.
14.1.2.6	Pumps, Circulators, and Fans	Devices for transporting cryogenic liquids and gases are need for many applications, such as propellant-tank mixing, cryogenic fluid transfer, broad-area cooling loops, etc.
14.1.2.7	Integrated Radiator/ Cryocooler for Liquefaction	High-capacity, high-efficiency, low-mass heat rejection system and controls for oxygen production on the Martian surface.
14.1.2.8	Subcooling Cryogenic Propellants	Allows extended storage time for cryogenic fluids post launch. Vent-free (on-ground) storage may also be possible with this technology.

Mid-temperature Technology Candidates –*Heat Acquisition*

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Table 6. TA 14.2.1 Technology Candidates – not in priority order

TA	Technology Name	Description
14.2.1.1	Freeze-Tolerant Heat Pipes	Heat transport devices that can freeze and thaw without damage or degradation in performance.
14.2.1.2	High-Flux Heat Acquisition with Constant Temperature	Micro- and nano-scale heat transfer enhancement technologies that use latent heat to maintain constant temperature.
14.2.1.3	Damage-Tolerant or Self-healing Electric Heaters	Advanced electro-resistive materials, including nanotechnology, and component design.
14.2.1.4	Insulation	Lightweight thermal insulators with low conductivity and effective emissivity (ε*).

Mid-temperature Technology Candidates –*Heat Transport*

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NASA

Table 7. 14.2.2 Technology Candidates – not in priority order

TA	Technology Name	Description
14.2.2.1	Heat Transport Fluid	Heat transport fluids that provide optimal thermo-physical properties for pumped loop acquisition, transport, and rejection while providing low toxicity to crew.
14.2.2.2	Advanced Pumps	Long-life pumps for circulating heat transfer fluids.
14.2.2.3	Heat Straps	Mechanical devices with extremely high thermal conductivity.
14.2.2.4	Heat Switches	Remotely-actuated mechanical or gas-based devices with high thermal conductivity on/off ratio.
14.2.2.5	Heat Pipe Capillary Based Loops	Closed, two-phase heat transfer loops serving multiple heat loads and rejecting to multiple thermal sinks, with tight temperature control and minimal temperature drops.
14.2.2.6	Heat Pump	Devises that use energy to transfer heat against a thermal gradient to reject heat to a higher temperature sink.
14.2.2.7	Thermal Electric Coolers (TECs)	Solid-state devices that use the Peltier effect to pump heat against a thermal gradient.
14.2.2.8	In-situ Thermal Fluids Chemical Analysis	In-situ thermal fluids chemical analysis to monitor thermal transport fluid health status.
14.2.2.9	High-thermal-conductivity Thermal Interface Materials	Advanced materials that can provide very high thermal interface conductance and yet also be workable. Vacuum compatible, and not degrade performance through repeated cycling.
14.2.2.10	Micro-/nano-scale Heat Transfer Surfaces	Advanced surface treatments to enhance the heat transfer coefficient and/or stability of heat exchangers in contact with a fluid.
14.2.2.11	Integrated Structural, Thermal, and Optical (STOP) Computer Software	Improved integration of existing software codes, or development of new codes and algorithms, for simulating optical alignment as a function of temperature and materials properties.

Mid-temperature Technology Candidates –*Heat Rejection and Storage*

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Table 8. TA 14.2.3 Technology Candidates – not in priority order

TA	Technology Name	Description
14.2.3.1	Radiator Surface Dust Control	Specialized passive coatings (or active control) that will reduce or eliminate dust on a radiator surface.
14.2.3.2	Two-Phase Pumped Loop System	Two-phase heat transport systems for thermal control of large heat loads, such as those required by Rankine cycle power plants.
14.2.3.3	Phase-Change Heat Exchanger - PCM (Thermal Storage) (heat sinks & storage)	Phase-change materials (PCM) used to store thermal energy during hot phases of cyclic thermal environments for later rejection during cold phases.
14.2.3.4	Evaporative Cooling	Evaporative cooling through water membrane evaporator.
14.2.3.5	Freezable/Stagnating Radiator (Variable Heat Rejection Radiator Technology)	Freezable or stagnating and flow-recoverable radiator fluid paths to allow spacecraft radiators to freeze during cold mission environments and predictably thaw for resumed operation in hot environments.
14.2.3.6	Variable-Geometry Radiators (Variable Heat Rejection Radiator Technology)	Variable-geometry radiators allow heat rejection turn-down by varying the radiating surface's view to the radiative heat sink.
14.2.3.7	Variable-Emissivity Radiator (Variable Heat Rejection Radiator Technology)	Material coatings or electrical layers that allow control of surface emissivity to manage radiated energy.
14.2.3.8	Radiator Repair	Equipment, materials, and processes required to repair spacecraft radiator systems in a space environment.
14.2.3.9	80-250°C Variable Conductance Heat Pipe Radiator	Heat pipe radiator for high-temperature heat rejection typically associated with nuclear power systems. Passive and variable heat rejection using variable conductance heat pipe technology.

Thermal Protection Systems Technology Candidates – *Ascent/Entry*

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Table 10. TA 14.3.1 Technology Candidates – not in priority order

TA	Technology Name	Description
14.3.1.1	Rigid Ablative TPS	Materials provide thermal protection from high-speed atmospheric aerothermal entry heating loads by pyrolysis of in-depth resins and surface ablation to protect the underlying spacecraft structure.
14.3.1.2	Obsolescence-Driven TPS Materials	Ascent thermal protection materials, such as Shuttle-era cryo-insulation, primers and ablators containing now-banned regulated or restricted materials such as HCFCs and hexavalent chromium, require replacement while continuing to meet technical performance requirements.
14.3.1.3	Flexible/Deployable TPS	Flexible heat shields for deployable systems provide higher heat flux capability to support a wider range of missions.
14.3.1.4	In-Space TPS Repair	Damage to space vehicle entry thermal protection systems resulting from ascent, on-orbit micrometeoroid and orbital debris exposure, and damage induced through other operation may compromise the ability of the TPS to adequately protect the vehicle and crew during atmospheric entry. Suitable repair technologies are required to restore capability to entry TPS.
14.3.1.5	TPS Integral Health Monitoring System (HMS)	A TPS with an integral HMS would reduce mission risk by automatic impact detection, localization, and evaluation.
14.3.1.6	Self-Repairing TPS Materials	TPS that can return to virgin state without external intervention using self-healing materials.
14.3.1.7	Multi-Functional TPS	A TPS that is not purely parasitic weight, as traditional systems would provide increased mass efficiency by incorporating other functions, like structural load-carrying capacity or cryogenic insulation.
14.3.1.8	High Temperature Seals and Thermal Barriers	High-temperature seals and thermal barriers.

Thermal Protection Systems Technology Candidates – *Modeling and Simulation*

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Table 11. TA 14.3.2 Technology Candidates – not in priority order

TA	Technology Name	Description
14.3.2.1	Coupled Multi-Dimensional Flow/Material Response/Thermal/Structural Analysis	Improved analysis techniques for TPS performance in flight and ground test environments will reduce analysis time and cost and improve the fidelity of the analysis, resulting in savings of TPS mass by reducing uncertainty.
14.3.2.2	Shock Radiation Modeling	Analytical modeling of entry shock radiance.

Thermal Protection Systems Technology Candidates – Sensors and Measurement Systems

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Table 12. TA 14.3.3 Technology Candidates – not in priority order

TA	Technology Name	Description
14.3.3.1	Radiometers/Spectrometers	Shock-layer radiation is a function of vehicle size and reentry velocity. The larger the vehicle, the higher the velocity and, consequently, the higher the heating. Measurements may also be useful on backshell TPS for Mars entry missions. Mars return missions, depending on the mission architecture, result in higher return velocities and therefore drive the need for these measurements.
14.3.3.2	High-Temperature Sensors – Wireless	Room-temperature wireless technology is commercially available, providing wireless distributed sensing for a variety of parameters, including temperature.
14.3.3.3	Temperature Sensors – Fiber Optic	Full-field temperature sensing using highly-multiplexed fiber Bragg gratings on optical fibers.
14.3.3.4	Non-Intrusive Recession and Temperature Sensors	Recession sensors measure the amount of recession and recession rate at a specific location in the TPS. Develop technology for non-intrusive measurement of both recession and temperature.

Conclusion

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- NASA Technology Roadmaps are instrumental in managing NASA's technology portfolio
- Identified needed technologies based on future missions identified by SMD, HEOMD, and ARMD
- Capability driven
- Created by NASA's senior SME's with broad input from practitioners

- Overview of the 2015 NASA Technology Roadmaps
  - Incorporated feedback from other government agencies, commercial sector and academia to improve development process and use with portfolio analysis.
  - Incorporated NRC recommendations from 2012 review
  - Expanded and enhanced from 2012 roadmaps
  - 2015 Roadmaps now Include crosscutting section and indexes
  - Very broad participation in update of technology roadmaps
  - Positive feedback on updated roadmaps

- NASA uses roadmaps frequently
  - Basis for portfolio prioritization
  - Portfolio analysis
  - Assessments and evaluations
  - Communication and partnership discussion
  - Solicitations
  - TechPort – communication of technology portfolio to the public

http://www.nasa.gov/offices/oct/home/roadmaps/index.html